Recent (<5 Ma) alluvial fans on Mars: formative processes and climatic implications

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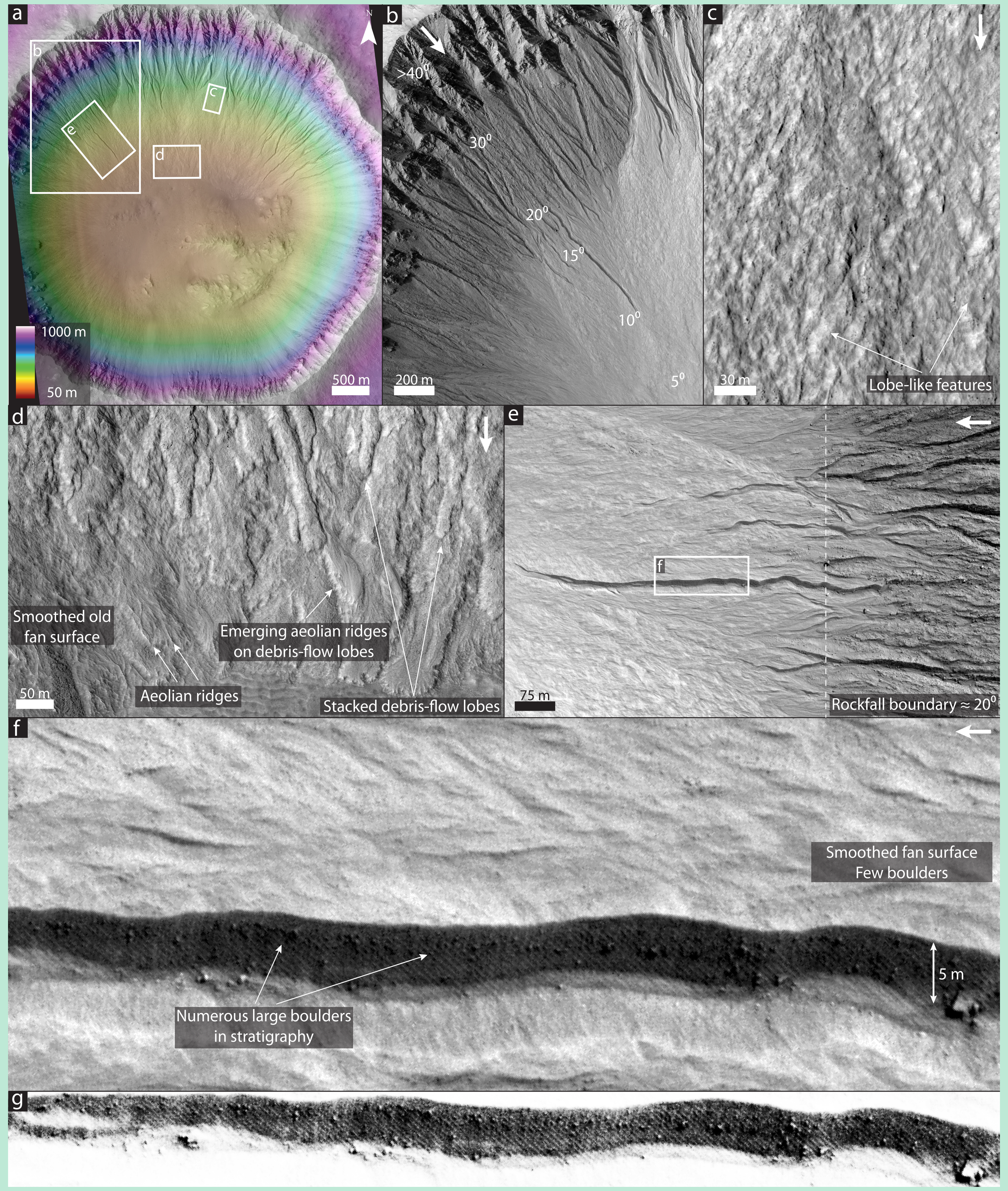
Introduction

Liquid water is currently extremely rare on Mars, but was probably more abundant during periods of high obliquity in the last few millions of years, testified by the widespread occurence of midlatitude gullies. Key to unraveling the planet's recent hydrologic and climatic conditions is determining the formative mechanisms of gullies: did they form by water-free sediment flows, debris flows and fluvial flows?

Objectives

We aim to determine (1) by which processes gullies were formed, (2) how much liquid water was involved in their formation and (3)how frequently liquid water occurred during high-obliquity periods.

Formative processes: Subsurface as the key to the surface



- Morphometric analyses of gullies imply a formation by debris flows.
- Debris-flow morphology is generally absent on Martian gullies; suggesting a formation by other processes.
- This controversy has been present in literature for over 15 years.
- Sedimentological analyses in outcrops of Martian gullies show that gullies were mainly formed by debris flows (Fig. 1):
  - Meter-sized boulders
  - Boulders dispersed in finer matrix
  - Lens-shaped and truncated layering
- More than 90% of the surfaces of fans with debris-flow evidence in stratigraphy do not show any debris-flow morphology.
- Fan surfaces are modified by secondary processes, mainly wind erosion and weathering.

Fig. 1) Morphometry, morphology and stratigraphy of depositional landforms in Galap crater. (a) Overview and digital elevation model of Galap crater. (b) Detail of northwestern slope showing gradients of catchment and depositional fan. (c) Detail of proximal fan surface. (d) Detail of distal fan surface. (e) Detail of fan surface with incised channels; note distinct difference in number of boulders below and above the rockfall boundary. (f) Example of stratigraphic section. (h) Same stratigraphic section as in f, but with optimized contrast in the section. Arrows denote downslope direction. HiRISE image PSP_003939_1420.

Unmodified debris-flow deposits: Istok crater

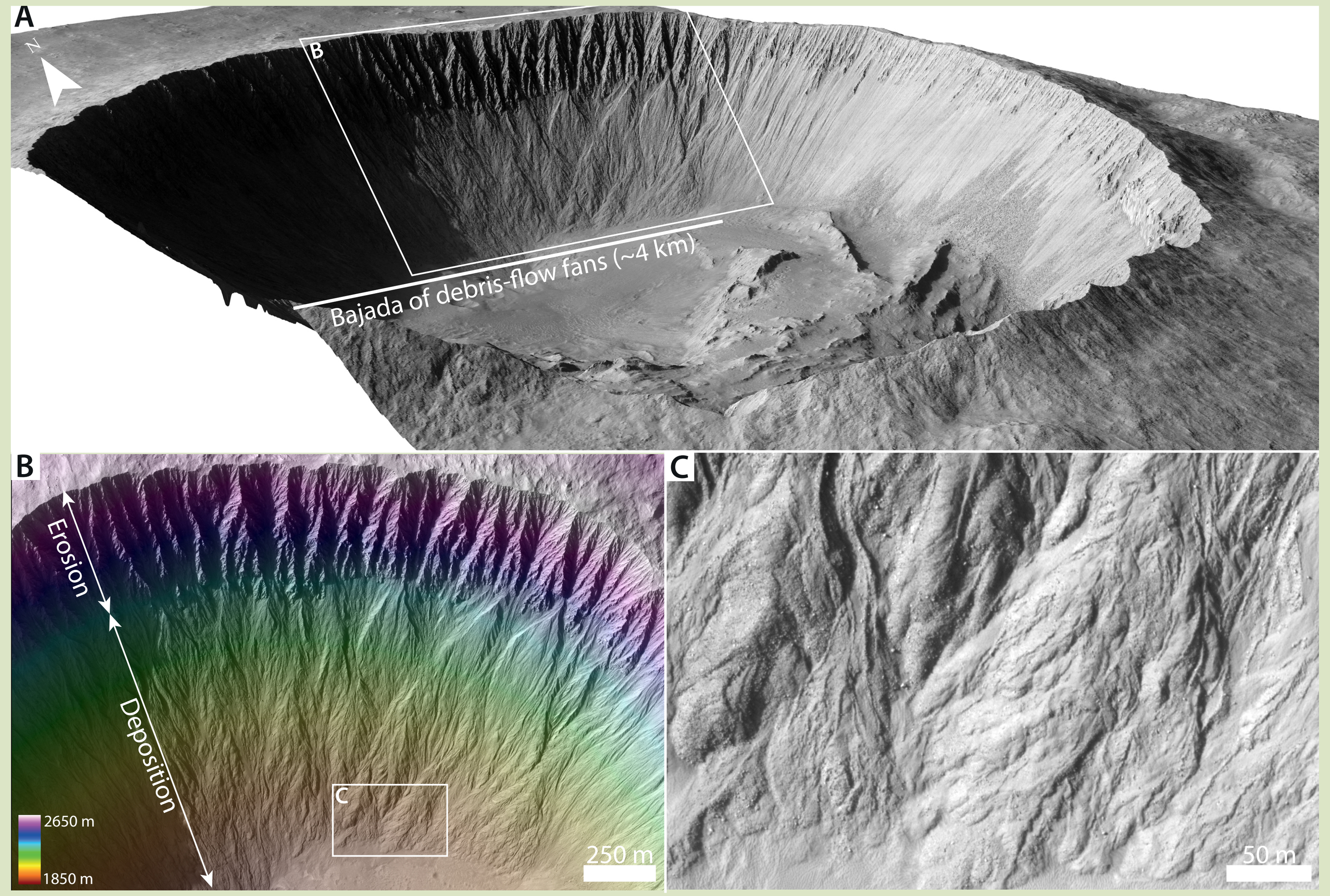


Fig. 2) Istok crater. (A) Bajada of remarkably pristine debris-flow fans on the pole-facing slope. (B) Eroding alcoves supply sediments to the downslope bajada of fans. (C) The fans are composed of debris-flow deposits, as testified by the widespread occurrence of paired levees, distinct depositional lobes and embedded boulders. Debris-flow volumes can be reconstructed from a digital elevation model (DEM). Currently, Istok crater is the only identified crater with unmodified debris-flow deposits and thus the only crater wherein detailed quantitative analyses can be performed (see below). HiRISE image: PSP_006837_1345.

Debris-flow volumes and return period

- Debris-flow return periods range between 1 to 200 yr depending on obliquity threshold for melting (Fig. 2).
- Millimeters to centimeters of liquid water averaged over the catchments are required for the formation of the observed debris flows. Snow/ice accumulations must have been centimeters to decimeters thick.

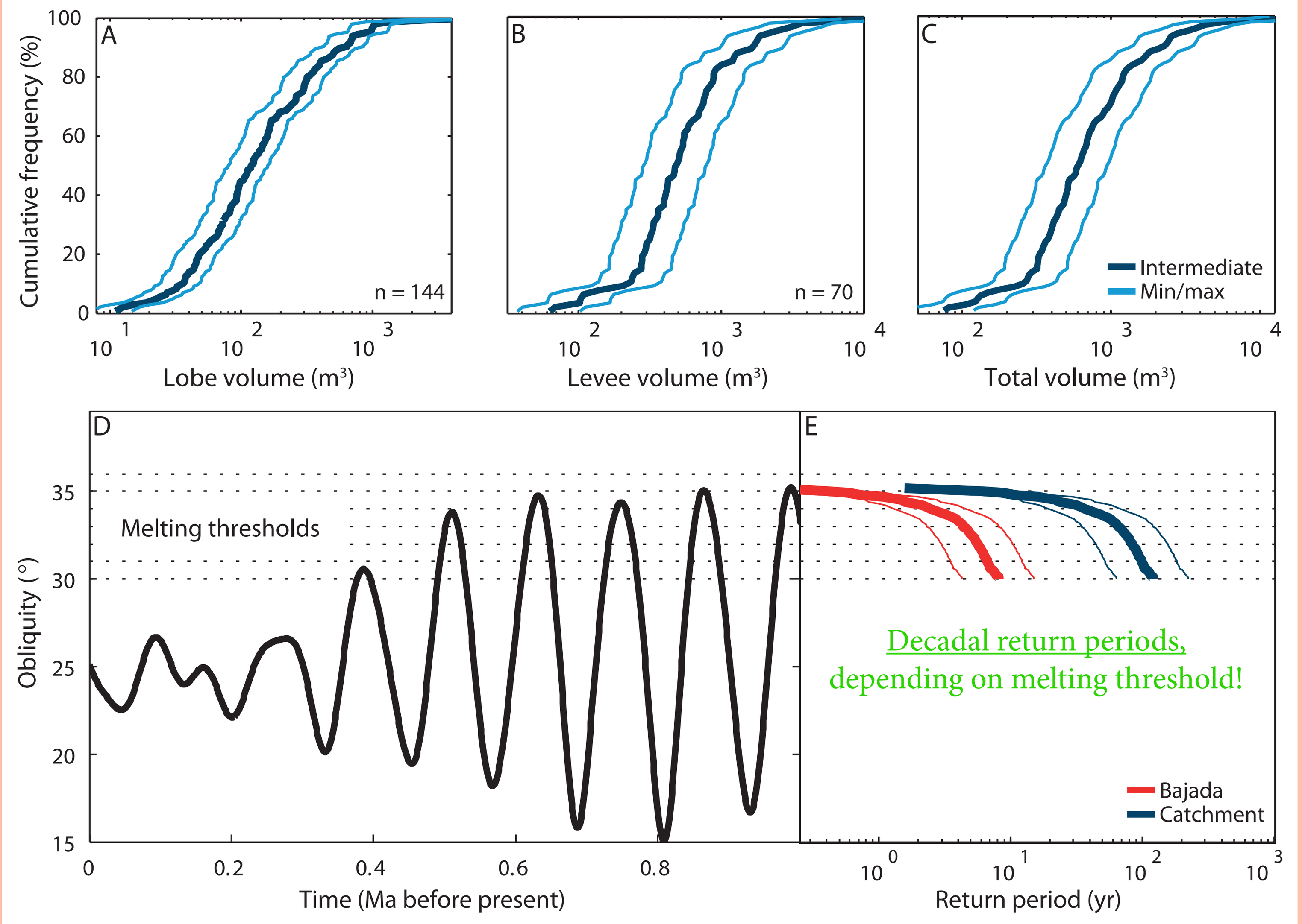


Fig. 3) Debris-flow return periods and size in Istok crater. (A) Cumulative frequency distribution of lobe volume. (B) Cumulative frequency distribution of levee volume. (C) Cumulative frequency distribution of total debris-flow volume (lobe and levee volume combined). (D) Obliquity in the last Ma on Mars, and potential thresholds for melting on mid-latitude pole-facing crater walls. (E) Debris-flow return periods on the bajada and per catchment. Istok crater formed 0.1-1 Ma ago (as inferred by crater counting). The number of debris flows that was required to form the bajada of gully-fans was derived by dividing the total bajada volume by the volume of the modal-sized debris flow as given in c. Minimum, maximum and intermediate estimate are derived by assuming a triangular, square or trapezoid lobe and levee shape, respectively.

Earth-like debris-flow frequency

Debris flows occurred at Earth-like frequencies during high-obliquity periods in Istok crater during the last million years on Mars (Fig. 4).

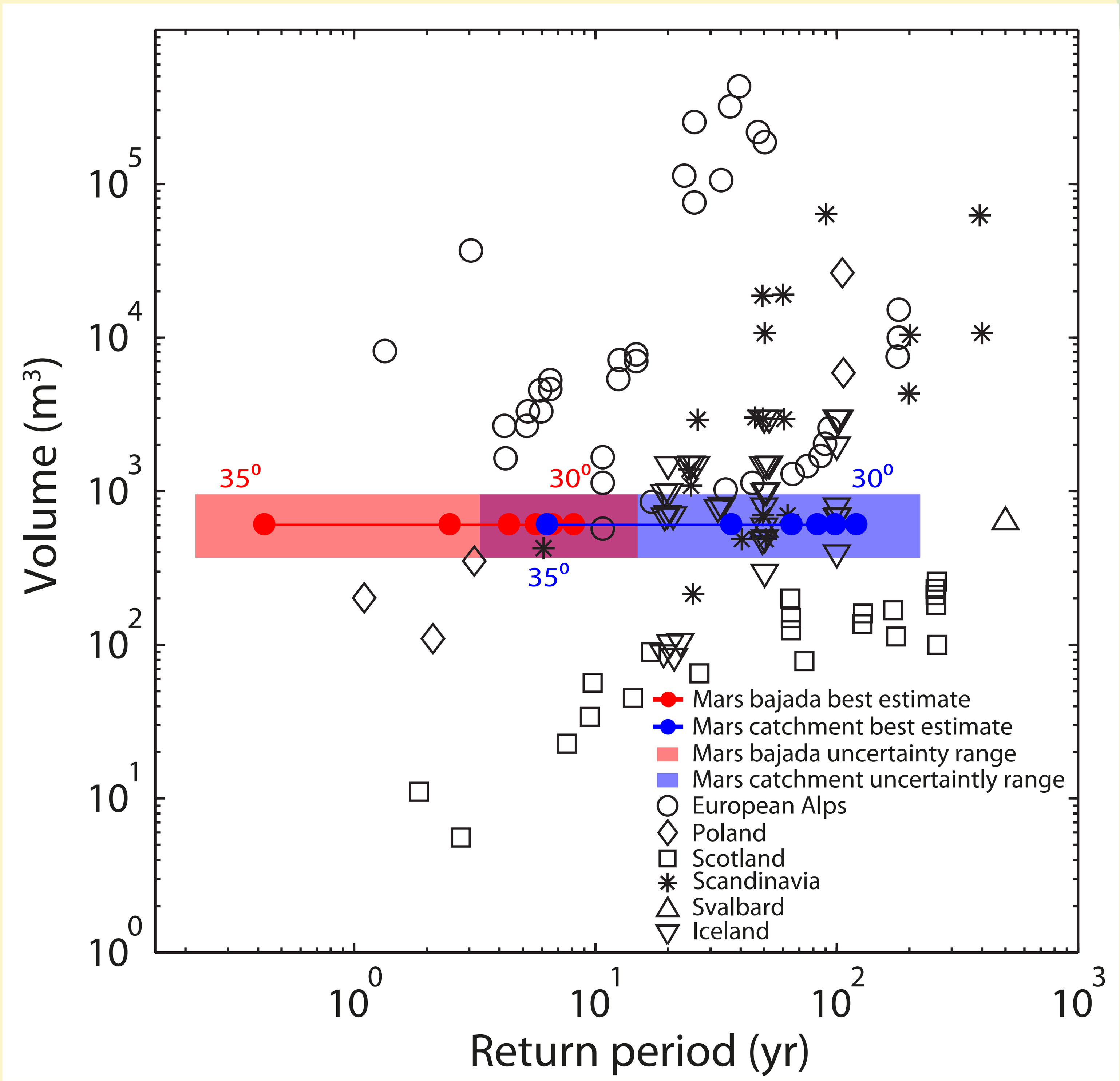


Fig. 4) Comparison between debris-flow volumes and return periods in Istok crater, Mars, and examples from Earth. The return periods on Mars are clearly within the range of return periods observed in temperate to polar regions on Earth regardless of the uncertainty in debris-flow volume, return periods per bajada or individual catchment and obliquity thresholds for melting between 30° and 35°.

Conclusions

- Recent small alluvial fans on Mars (i.e., gullies) are mainly formed by debris flows.
- Debris-flow morphology is generally absent on gully-fan surface due to secondary modification by weathering and erosion.
- Debris flows occurred at Earth-like frequencies in Istok crater during high-obliquity periods in the last million years on Mars.
- Millimeters to centimeters of liquid water, and centimeters to decimeters of snow, averaged over the catchments were required to form the observed debris flows.

Publications: (1) De Haas, T., Hauber, E., Conway, S. J., van Steijn, H., Johnsson, A. & Kleinhans, M. G., Earth-like aqueous debris-flow activity on Mars at high orbital obliquity in the last million years. Nature Communications (2015), DOI:10.1038/ncomms8543. (2) De Haas, T., Ventra, D., Hauber, E., Conway, S. J., Kleinhans, M. G., Sedimentological analyses of Martian gullies: the subsurface as the key to the surface. Icarus (2015), 258, 92-108.
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